

## Study of QGP with probes associated with photon at RHIC-PHENIX

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When heavy ions with high energy collide, a hot and dense matter is produced. As the matter expands, the matter undergoes cross-over phase transition from partonic matter to hadronic matter. Jets are created by high  $p_T$  partons in the early phase of the collisions. Leptons and photons can penetrate the matter without strong interaction. For that reason, jets, leptons and photons are good probes to study the partonic matter in the early phase of the collisions. We report about two probes associated with photon and their results for PHENIX.

### 1 High $p_T$ neutral pions

#### 1.1 Measurement of the initial density in the matter

It has been observed in central Au+Au collisions at Relativistic Heavy Ion Collider (RHIC) that the yield of neutral pion at high transverse momentum ( $p_T > 5$  GeV/c) is strongly suppressed compared to the expectation from  $p + p$  collisions scaled by the number of binary collisions (Jet quenching). This suppression is regarded due to the energy loss of hard scattered partons in the medium, which results in a decrease of the yield at a given  $p_T$ . Many theoretical models have been proposed to understand the parton energy loss mechanism. GLV method<sup>1</sup> as one of the calculations predicts that the magnitude of energy loss is proportional to the square of the path length. Therefore measuring the path length dependence of energy loss should improve our knowledge on energy loss constrain the parton energy loss models.

#### 1.2 Neutral pion production with respect to the reaction plane

To quantify the energy loss in the matter, we introduce the nuclear modification factor ( $R_{AA}$ ).

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}, \quad (1)$$

where  $N^{AA}$ ,  $\sigma^{NN}$  and  $T_{AA}$  are yields of neutral pion in Au+Au collisions, the cross section of neutral pion ( $p + p$ ) and the nuclear overlap function calculated by Glauber model, respectively. The path length can be estimated by measuring the azimuthal angle from reaction plane and the impact parameter (centrality). Therefore the  $R_{AA}$  for each azimuthal angle ( $\Delta\phi_i$ ) bin is measured to obtain the path length dependence of  $\pi^0$  production. The  $R_{AA}(p_T, \Delta\phi)$  is derived by the following equations.

$$R_{AA}(p_T, \Delta\phi_i) = R_{AA}(p_T) \times \frac{N(p_T, \Delta\phi_i)}{\sum_{\phi_i} N(p_T, \Delta\phi_i)} \quad (2)$$

$$N(p_T, \Delta\phi_i) \propto 1 + 2v_2 \cos(2\Delta\phi_i) \quad (3)$$

The second harmonic term ( $v_2$ ) means the azimuthal anisotropy. The anisotropy  $v_2$  at low  $p_T$  creates collective flow and the flow is background for measuring the  $R_{AA}(p_T, \Delta\phi)$ . In order to reduce the effect of collective flow, we measure the yields at higher  $p_T$ . Figure 1 shows the anisotropy  $v_2$  of neutral pion as a function of  $p_T$  for each 20 % centrality class. These values are non-zero for all centrality classes. Additionally, assumed linear and constant functions are fitted to this data and the fit results are shown in Table 1. These results indicate that the anisotropy  $v_2$  of neutral pion in most central and peripheral collisions tends to be constant, while in mid-central collisions it tends to decrease.

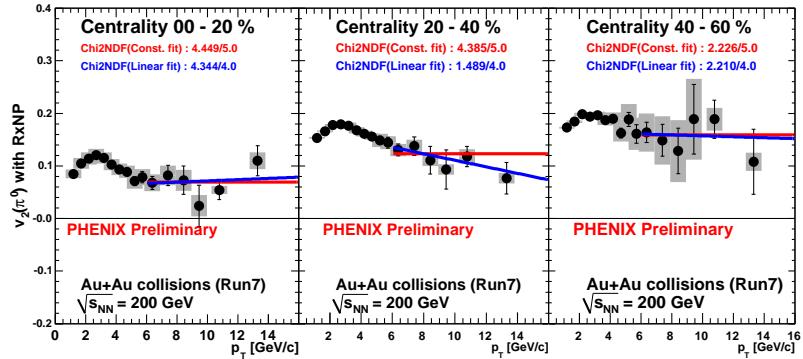


Figure 1: The anisotropy  $v_2$  of neutral pion as a function of  $p_T$  for each 20 % centrality class. Red and blue lines which are fitted to the data from 6  $\text{GeV}/c$  show constant and linear fit function, respectively.

Centrality [%]	Constant ( $\chi^2/\text{NDF}$ )	Linear ( $\chi^2/\text{NDF}$ )
00–20	4.45/5	4.34/4
20–40	4.39/5	1.49/4
40–60	2.23/5	2.21/4

Table 1: Fit results with the two functions for three centrality classes.

### 1.3 Comparison of $R_{AA}(p_T, \Delta\phi)$

Recently theoretical models (ASW<sup>2</sup>, HT<sup>3</sup> and AMY<sup>4</sup>) which involve the space-time evolution of the matter have been proposed to investigate parton energy loss mechanism<sup>5</sup>. The left panel of Fig. 2 shows these models succeed in reproducing the centrality dependence of  $R_{AA}(p_T)$ . The central and right panels show the theoretical curves and the measured data at the same centrality class, respectively. These models are still unable to reproduce the measured  $R_{AA}(p_T, \Delta\phi)$ .

## 2 Low $p_T$ direct photon

### 2.1 Measurement of the initial temperature of the matter

Thermally equilibrated matter is expected to radiate thermal photons, whose kinematics ( $p_T$  or yield) is sensitive to the temperature of the matter. Thermal photons are predicted to be dominant in direct photons for low  $p_T$  ( $1 < p_T < 3 \text{ GeV}/c$ ) in Au+Au collisions. On the other hand, a huge background is also produced by decay photons at this  $p_T$  region. Electron pairs via virtual photon have been measured by the PHENIX experiment in order to improve the signal to background and associated systematic errors<sup>8</sup>.

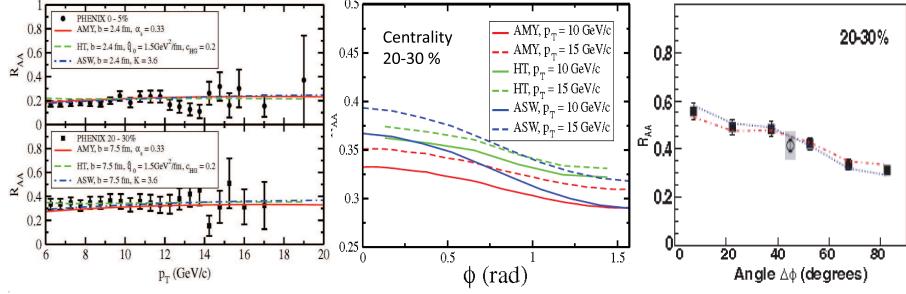


Figure 2: Left:  $R_{AA}(p_T)$  at centrality 0-5 % (top) and 20-30 % (bottom) calculated in three models compared with the data. Central:  $R_{AA}(p_T, \Delta\phi)$  at  $p_T = 10$  GeV/c (solid line) and  $p_T = 15$  GeV/c (dashed line) for three models at centrality 20-30 %. Right:  $R_{AA}(p_T, \Delta\phi)$  at  $5 < p_T < 8$  GeV/c at centrality 20 – 30%.

## 2.2 Low mass $e^+e^-$ via internal conversion

In general, any source of real photons can emit virtual photons and the virtual photons can convert to low mass  $e^+e^-$  pairs. The relation of real photon production and  $e^+e^-$  pair production can be derived by Knoll-Wada formula<sup>7</sup> based on quantum electrodynamics (QED). Figure. 3 shows mass spectra of  $e^+e^-$  pairs in  $p + p$  and Au+Au collisions for several  $p_T$  ranges. These mass spectra are compared to expected yields from a cocktail of the hadron decay calculation. This cocktail calculation is based on meson production as measured by PHENIX. The  $p + p$  data are consistent with the cocktail for low  $p_T$  region, while they have a small excess for high  $p_T$  region. The Au+Au data are good agreement with the cocktail for  $M_{ee} < 50$  MeV/ $c^2$  and the excess of the yields have much larger than  $p + p$  for all  $p_T$  bins.

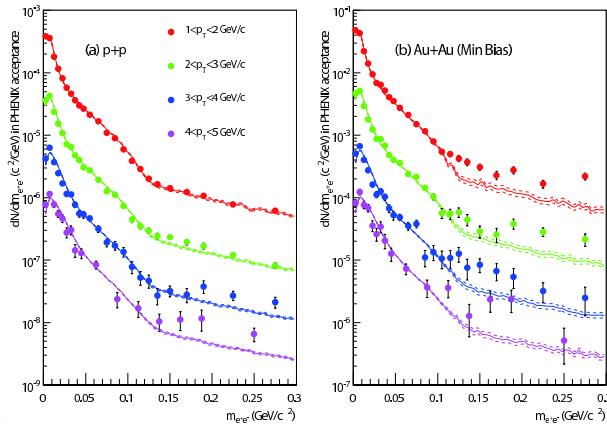


Figure 3: Left:  $e^+e^-$  pair invariant mass distributions in (a)  $p + p$  and (b) minimum bias Au+Au collisions, respectively. The  $p_T$  ranges are shown in the legend. Solid and dashed lines represent the expected values from the cocktail calculation and their systematic uncertainties, respectively.

Red, blue and green lines show next-to-leading-order perturbative quantum chromodynamics (NLO pQCD) calculations which include theoretical scales for  $\mu = 0.5 p_T$ ,  $p_T$  and  $2 p_T$ , respectively. The  $p + p$  data are consistent with the expectation from NLO pQCD calculations, while the clear enhancement for the Au+Au data is shown at  $p_T < 3.5$  GeV/c. The direct photon invariant yield is extracted from the fraction of the direct photon yield and the inclusive photon yield. Figure. 4 shows the invariant cross section of photon in  $p + p$  and as a function of  $p_T$  in  $p + p$  and the invariant yield for several centrality classes in Au+Au collisions. The filled and open points are from virtual photon analysis and from the Ref. 10,11, respectively. The three curves on the  $p + p$  data represent NLO pQCD calculations and the dashed lines show modified power-law fit to the  $p + p$  data, scaled  $T_{AA}$ .

The black lines are exponential plus the  $T_{AA}$ -scaled  $p + p$  fit. The NLO pQCD calculation is consistent with the  $p + p$  data within theoretical uncertainties for  $p_T > 2$  GeV/c. As shown in Fig. 4, the  $p + p$  data can be well described by a modified power-law fit function ( $A_{pp}(1 + p_T^2/b)^{-n}$ ). Furthermore, we fit an exponential plus the  $T_{AA}$ -scaled modified power law function ( $Ae^{-p_T/T} + T_{AA} \times A_{p+p}(1 + p_T^2/b)^{-n}$ ) to the direct photon invariant yield in Au+Au collisions. Here  $T_{AA}$  is the nuclear overlap function and the free parameters are  $A$  and the inverse

slope  $T$ . This inverse slope  $T$  is closely related to the temperature in the matter. The obtained  $T$  from the fit is  $221 \pm 23 \pm 18$  MeV for central Au+Au collisions. This value is beyond the critical temperature ( $T_c$ ) expected from lattice QCD ( $T_c \approx 170$  MeV). The right panel of Fig. 4 shows the comparison of invariant cross section for Au+Au central collisions and the direct photon spectra obtained by several hydrodynamical calculations<sup>9</sup>. Hydrodynamical calculations assume initial temperature ranging from  $T_{init} = 300$  MeV at thermalization time  $\tau_0 = 0.6$  fm/c to  $T_{init} = 600$  MeV at  $\tau_0 = 0.15$  fm/c. These models can reproduce the central Au+Au collisions (centrality 0 – 20%) data within a factor of two.

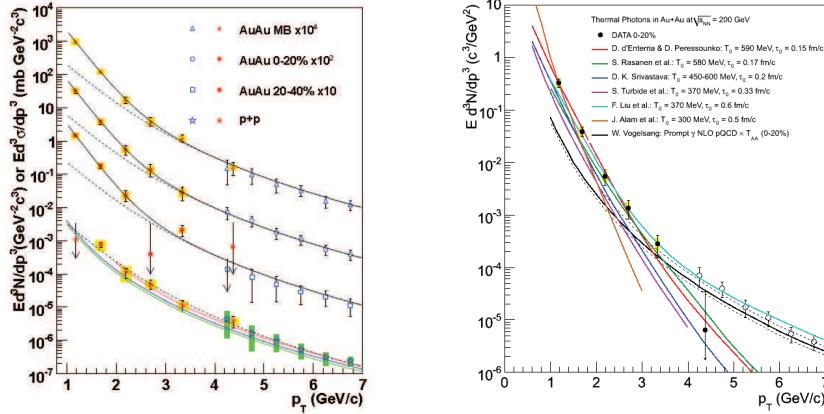


Figure 4: The left panel shows invariant cross section ( $p + p$ ) and invariant yield (Au+Au) of direct photon as a function of  $p_T$ . The right panel shows invariant cross section for Au+Au collisions (centrality 0 – 20%) and several calculations.

### 3 Summary

The probes associated with photon are a powerful tool to study the property of hot and dense matter. For studying parton energy loss mechanism, path length dependence of the energy loss for high  $p_T$  hadrons is expected to strongly constrain the parton energy loss calculations. The azimuthal anisotropy  $v_2$  of neutral pion is measured for three centrality classes and their values at high  $p_T$  are finite. Theoretical calculations succeed to reproduce the centrality dependence of  $R_{AA}(p_T)$ , however azimuthal angle dependence of  $R_{AA}$  can not still be reproduced. For measuring the initial temperature of the matter,  $e^+e^-$  pairs through internal conversion are measured at  $1 < p_T < 5$  GeV/c. The enhancement is clearly observed in Au+Au minimum bias events for  $1 < p_T < 5$  GeV/c. The  $T_{AA}$ -scaled  $p + p$  fit function is fitted to the direct photon spectrum for the central Au+Au collisions. The obtained inverse slope from the fit is  $T = 221 \pm 23(\text{stat.}) \pm 18(\text{sys.})$ . This is beyond the temperature of a phase transition which lattice QCD predicts.

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